A STRONG TEST OF ELECTRO-WEAK THEORY USING PULSATING DB WHITE DWARF STARS AS PLASMON NEUTRINO DETECTORS

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ABSTRACT

We demonstrate that plasmon neutrinos are the dominant form of energy loss in model white dwarf stars down to $T_{\rm eff} \sim 25,000$ K, depending on the stellar mass. The lower end of this range overlaps the observed temperatures for the V777 Her star (DBV) instability strip. The evolution of white dwarfs at these temperatures is driven predominantly by cooling, so this directly affects the stellar evolutionary timescale in proportion to the ratio of the neutrino energy loss to the photon energy loss. This evolutionary timescale is observable through the time rate of change of the pulsation periods. Although the unified electro-weak theory of lepton interactions that is crucial for understanding neutrino production has been well tested in the high energy regime, the approach presented here should result in an interesting low-energy test of the theory. We discuss observational strategies to achieve this goal.

Subject headings: neutrinos—stars: interiors—stars: oscillations—white dwarfs

1. INTRODUCTION

Not long after Fermi's theory of the weak interaction was first generalized to include, among other things, the possibility of a direct interaction between the electron and the relevant neutrino (e.g., Feynman & Gell-Mann 1958), a variety of theoretical papers pointed out that this interaction, though extremely feeble, could have a major impact in the hot dense plasmas to be found in the astrophysical domain (see Fowler & Hoyle 1964, for an early review). However, given the weakness of neutrino interactions, direct measurements of these rates in astrophysical objects have proved a great challenge. These measurements rely on enormous detecting volumes in order to obtain a significant number of events. In fact, only in the case of the Sun and SN 1987A have direct links been made between detections of neutrinos and particular astronomical objects.

It is possible to measure neutrino rates, albeit indirectly, in a third class of objects, the white dwarf stars. For both the hot white dwarf and a pre-white dwarf stars the theoretical neutrino energy losses exceed the photon energy losses, and so essentially control the evolutionary timescale. The astrophysical significance of neutrino emission in hot pre-white dwarf stars has been investigated extensively by many authors, building on the foundations of work undertaken at the University of Rochester (e.g. Vila 1966; Kutter & Savedoff 1969; Savedoff, Van Horn & Vila 1969). The principal observable signature of these neutrinos was thought to be in the white dwarf luminosity function (e.g., see Lamb & Van Horn 1975). In the mid-eighties we (e.g., Kawaler, Winget, & Hansen 1985) demonstrated that evolutionary frequency drifts in the non-radial gravity modes present in pulsating hot pre-white dwarf (DOV) stars might provide a very sensitive

probe of plasmon neutrino emissions in just the temperature range where the neutrino luminosity was near its maximum. We later reported the observational detection of an evolutionary rate of period change for one DOV, PG 1159-035 (Winget et al. 1985; Costa, Kepler, & Winget 1999), but the theoretical interpretation of this result remains elusive (see O'Brien & Kawaler 2000, for a recent summary). Theoretical models for PG 1159-035 have been unable to reproduce the observed period structure and the rate of period change simultaneously. Since the mechanical and thermal structure is more closely coupled than in cooler white dwarf stars, it is more difficult to identify the source of this problem.

No such difficulties should arise for the helium atmosphere DBV white dwarfs, since their cooler temperatures lead to greater degeneracy and hence a decoupling of their thermal and mechanical structure (see section 3.1 below). As a consequence, we should be able to measure the plasmon neutrino flux from these objects, testing the calculations of Itoh et al. (1996) and measuring the net effect of plasmon neutrinos.

2. PLASMON NEUTRINOS

Of the many possible neutrino emission processes, it is the plasmon neutrino process that dominates neutrino production in hot white dwarf interiors—the bremsstrahlung process comes a distant second. The existence of plasmon neutrinos is an important test of our understanding of the universality of the weak interaction. The nature of the process that creates them is well described by Clayton (1968), and we summarize it here.

A free photon cannot decay into a neutrino and an anti-neutrino because the constraint of coupling to a spin-1 particle requires the neutrinos to be emitted in opposite directions; as a result, energy and momentum cannot simultaneously be conserved and the process is forbidden. A photon propagating in a plasma does not have this problem—it conserves both energy and momentum by coupling to the plasma; such a coupled photon is referred to as a "plasmon". A plasmon with sufficient energy can decay into a neutrino and an anti-neutrino; the neutrinos created in this process are termed plasmon neutrinos:

$$\gamma^* \rightarrow \nu + \bar{\nu}.$$

Under normal stellar conditions, including white dwarf inte-

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riors, we expect the neutrinos created in this way to leave the star without further interaction, resulting in net energy loss.

For a physical picture of what a plasmon actually is, we can consider the photon to be a classical electromagnetic wave moving through a dielectric medium. If ω is the frequency of the photon, then we have

$$\omega^2 = k^2 c^2 + \omega_0^2,$$

where ω_0 is the plasma frequency. Since $E = \hbar\omega$ and $p = \hbar k$ for a photon, this can be re-written as

$$E^2 = p^2 c^2 + m_{\rm pl}^2 c^4,$$

where

$$m_{\rm pl} = \frac{\hbar\omega_0}{c^2}$$

acts as the effective mass of the plasmon. Thus, the plasmon behaves like a particle with a non-zero rest mass, and it is this effective mass that enables it to decay into a neutrino and anti-neutrino pair.

The size of this "rest mass" energy, $\hbar\omega_0$, is important for two reasons. First, in a general stellar environment these plasmon states will be in thermal equilibrium with their surroundings, so significant numbers of plasmons will be excited only if the typical thermal energy, $k_B T$, is larger than the plasmon energy, $\hbar\omega_0$. Second, the amount of energy liberated by the decay of a plasmon is related to its mass, with high mass plasmons liberating more energy than low mass ones. In low density non-degenerate gases, the plasma frequency is given by

$$\omega_0^2 = \frac{4\pi n_e e^2}{m_e},$$

and we typically find that $\hbar\omega_0 \ll k_B T$. Thus, even though there are many plasmons, their rest mass energy is so small that their decay releases little energy. In the dense plasmas of degenerate stellar interiors the plasma frequency, now given approximately by

$$\omega_0^2 = \frac{4\pi n_e e^2}{m_e}\left[1 + \left(\frac{\hbar}{m_e c}\right)^2 \left(3\pi^2 n_e\right)^{\frac{2}{3}}\right]^{-\frac{1}{2}},$$

is much larger, and plasmon neutrino production can lead to significant energy loss. However, if the density is too large then only the highest energy fluctuations out on the thermal tail will be large enough to excite plasmons, leading to a suppression of energy losses through neutrino emission.

This has important observational consequences. Theoretical evolutionary calculations show that for temperatures greater than $T_{\rm eff} \sim 35,000\,{\rm K}$ (see Figure 1a), the ratio of neutrino to photon luminosity is highest for massive white dwarf models. Higher plasma frequencies result from higher central densities in more massive pre-white dwarf models, yielding higher plasmon energies and correspondingly higher neutrino energy fluxes. Eventually, as the models cool, the thermal energies become too small for photons to excite plasmons. This happens first for the more massive model, and accounts for the fact that the neutrino rates of the less massive models dominate for temperatures less than 35,000 K. For the temperature range in which we are most interested, the DBV instability strip, neutrino losses still dominate for models with masses near the typical mass of the white dwarf stars, while they are completely negligible for the more massive models.
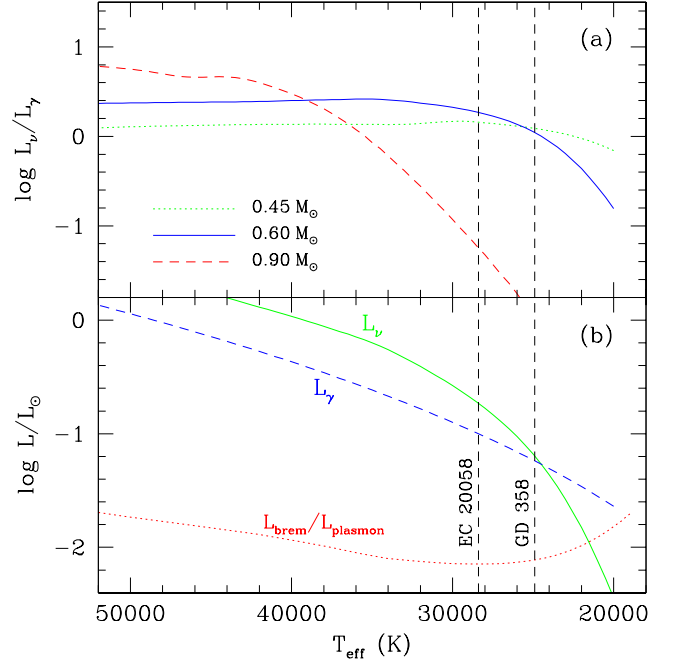

FIG. 1.— (a) the ratio of neutrino to photon luminosity for white dwarf models of various stellar mass. In the region of interest (near the temperatures of the pulsators GD 358 and EC 20058), neutrino losses for the high-mass models are negligible, while they are very significant for the less massive models. (b) The photon (dashed line) and neutrino (solid line) luminosities for a $0.6 M_\odot$ white dwarf, along with the fractional contribution of bremsstrahlung neutrinos (dotted line). The neutrino luminosity is nearly twice the photon luminosity at the temperature of EC 20058, and the two are approximately equal at the temperature of GD 358. The neutrino luminosity in this range is almost entirely due to the plasmon reaction.

3. EVOLUTIONARY CALCULATIONS

For the present work, we have computed several white dwarf evolutionary sequences in order to explore the effects of plasmon neutrinos in the DBV temperature range. We have calculated sequences using polytropic starting models as well as full evolutionary sequences calculated from various main-sequence progenitor models, including different parametric treatments of mass loss. As has been well established by numerous authors (e.g. Kawaler, Winget, Iben, & Hansen 1986), the thermal history is erased by the time these models cool to 35,000 K and the model sequences become indistinguishable for our purposes. We have calculated sequences with and without plasmon neutrino emission included, using the rates of Itoh et al. (1996) in our models (see Figure 1). At the energies relevant to our calculations, the difference between these newer rates and the older Beaudet, Petrosian, & Salpeter (1967) rates are $\sim$10 percent. For more complete details about the computation of the models, see Metcalfe, Nather, & Winget (2000).

3.1. Period Structure

The problem of the coupling of the mechanical and thermal structure, prominent in the DOVs, is nearly nonexistent by the time the models reach the temperature domain of the DBV stars. For example, we calculated the periods of models with $T_{\rm eff} \sim 28,000$ K from two sequences: a sequence including plasmon neutrino energy losses, and a sequence with the neutrino production rates set to zero. The differences between the corresponding pulsation periods of these models were always
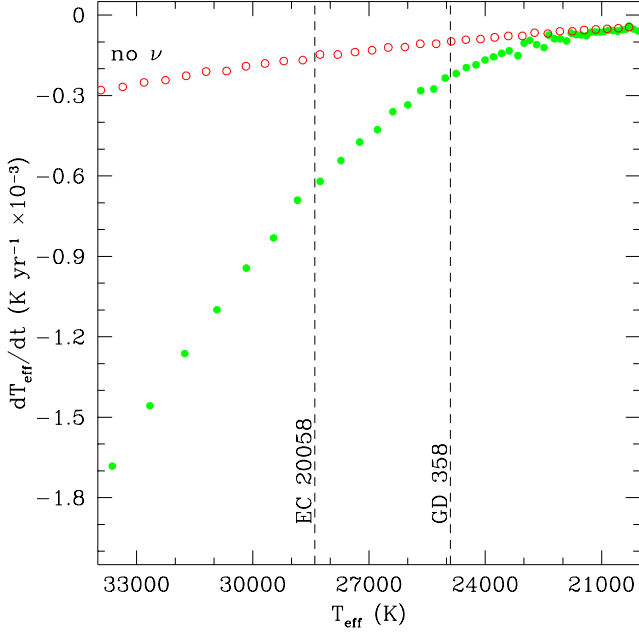
FIG. 2.— The rate of change of the effective temperature for white dwarf models that include (solid points) and ignore (open points) neutrino energy losses. The effective temperatures of two pulsating white dwarfs are shown as dashed lines. The models differ by a factor of 4 at the temperature of EC 20058 and a factor of 2 at the temperature of GD 358.
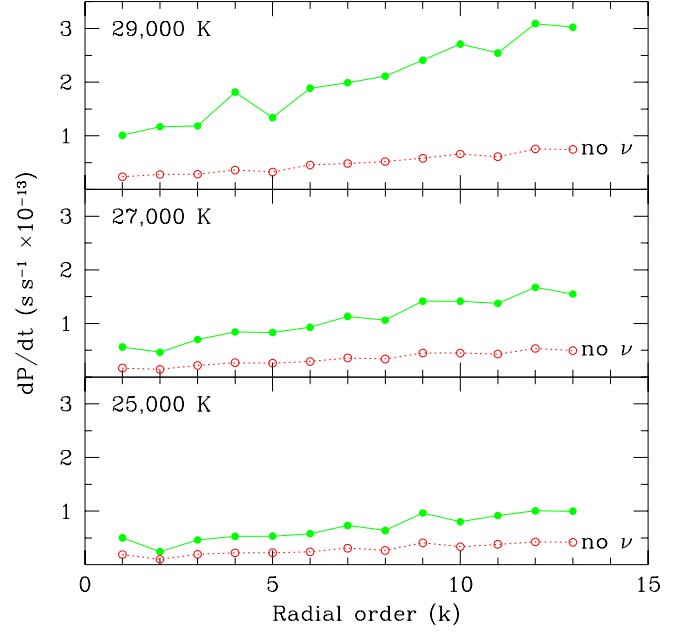

FIG. 3.— The rate of change for pulsation periods in models on the hot end of the DBV instability strip, including (solid points) and ignoring (open points) the effects of neutrinos. An observational measurement of the rate of period change for hotter DBV stars should allow us to detect the signature of neutrino emission.

$\lesssim 1$ second, with a typical difference of 0.24 seconds. We note that current uncertainties in the interior mechanical structure, such as the detailed C/O abundance profiles and the "double-layered" envelopes discussed by Fontaine & Brassard (2002) and Metcalfe, Montgomery & Kawaler (2003), only affect the periods at this same level of 1 second or less.

The energy loss to plasmon neutrinos primarily results in a reduced central core temperature compared to models without neutrinos (for the case considered above, this reduction in core temperature was ~20 percent). The pulsation periods are only slightly affected because the Brunt-Väisälä frequency is small in the core, where the pressure support is dominated by the strongly degenerate electrons. As a consequence, the g-mode pulsations are largely insensitive to the thermal structure in the core, which is the only thing that changes dramatically as a result of plasmon neutrino production.

3.2. *Rates of Period Change*

Although the change to the thermal structure due to plasmon neutrinos does not significantly alter the period structure, it does have a significant effect on DBV models; it shortens the evolutionary timescale in the temperature range 30,000 K $\gtrsim T_{eff} \gtrsim$ 25,000 K. This is easily seen in Figure 2, where we show the effect of plasmon neutrinos on the time rate of change of the effective temperature. The dashed lines indicate the temperature estimates of Beauchamp et al. (1999) for two DBV stars: the hotter one is EC 20058−5234, and the cooler one is GD 358. This should correspond roughly to the hot half of the DBV pulsation instability strip (Bradley & Winget 1994).

Although the temperature of EC 20058 deduced by Beauchamp et al. (1999) is relatively uncertain due to a poor quality spectrum, a comparison of the observed periods in the two stars provides independent asteroseismological evidence that EC 20058 is significantly hotter than GD 358. This is be-

cause the dominant pulsation periods in a white dwarf should be tracers of the thermal timescale at the base of the partial ionization/convection zone. Since the observed periods are much shorter in EC 20058 than in GD 358, EC 20058 should have a shallower convection zone, and hence a higher effective temperature (e.g., see Winget 1998, and references therein).

At these effective temperatures the evolution is dominated by cooling, with gravitational contraction playing a diminishing role. The cooling depletes the thermal energy stored in the ions. In models that include neutrinos, the thermal energy deep in the core is further depleted by the emission of plasmon neutrinos, and the evolutionary timescale is shorter than in models that ignore the effects of neutrinos. Figure 2 makes it clear that the effect of the plasmon neutrinos on the evolution is *not subtle*. Near the high temperature end of the observed DBV instability strip the evolutionary timescales of the models differ by a factor of about four, and by the middle of the instability strip they still differ by a factor of two.

This suggests that measurement of the evolutionary period change in hot DBV white dwarf stars would make an excellent probe of the plasmon neutrino production rates. As a proof of principle, we show in Figure 3 the rates of period change for theoretical evolutionary models with temperatures in the hot half of the DBV instability strip.

We have already established that model uncertainties at the current level do not alter the individual periods in a significant way for these measurements, and Figure 3 shows that exact radial order identification is also unnecessary. If we know the observed period and the spherical harmonic degree of a mode, then we can determine the radial order within ±1, which corresponds to a period range of 60–80 s for models with masses near $0.6 M_\odot$. For a typical range of periods, this gives us sufficient information to measure the plasmon neutrino production rates with a precision of ~10 percent. We note that the these

values are only sensitive to spherical harmonic degree (ℓ) at $\lesssim 10$ percent: the difference between $\ell = 1$ and $\ell = 2$ for the same period is ~ 10 percent, and the difference between $\ell = 2$ and $\ell = 3$ is $\lesssim 1$ percent.

4. DISCUSSION

Our work demonstrates the potential of directly measuring the effect of plasmon neutrino energy loss rates in the hot DBV white dwarf stars. Currently only one known DBV, EC 20058−5234, has both the high temperature and period stability necessary to measure an evolutionary period change. After its discovery by Koen et al. (1995), this object was observed in a 1997 multi-site Whole Earth Telescope campaign (XCOV15, Sullivan et al. 2003), with regular single-site observations since then (Sullivan 2003). Work on this particular object is in progress, but to fully exploit the potential of the DBV stars as plasmon neutrino detectors we need to undertake a comprehensive research program that includes the following components.

First, it will be important to expand the sample of known DBV stars well beyond the 9 currently known. This should provide access to a selection of hot DBV pulsators that have the required period stability for measuring evolutionary period changes. Fortunately, this goal appears to be feasible using candidate white dwarfs identified in the Sloan Digital Sky Survey, as has been adequately demonstrated by the recent large increase in the number of known DAV stars using this source (Mukadam et al. 2003).

Second, we must obtain better effective temperatures for the hot DBV stars of interest. Although not as important, it will also be useful to identify the ℓ values of relevant pulsation modes. Appropriate HST observations will be an important factor here. Both Figure 2 and Figure 3 indicate that the more accurately we can determine the temperature, either astero-

seismologically, spectroscopically, or both, the better limits we can place on dP/dt. The model rates of period change also depend on the pulsation mode ℓ value, so knowledge of this index will minimize the uncertainties.

Third, the overall program will be strengthened by access to a range of DBVs with different masses. Figure 1a shows that massive white dwarf stars (~ 0.9 M$_\odot$) are not producing significant plasmon neutrinos in this temperature range, and so can serve as a control. The rates of period change for these stars should be insensitive to plasmon neutrino production rates. In this way they will allow us to calibrate out any possible systematic effects. Comparative plasmon neutrino fluxes will also allow us to calibrate the fluxes as a function of density, and therefore plasmon energy.

Fourth, we need to undertake long-term photometric campaigns (in addition to the on-going EC 20058 observations) on suitable DBV candidate stars. We estimate that an observational timebase of between three and six years duration, depending on individual timing accuracies, will be required to achieve the goal of observing the predicted rates of period change. Two-meter class telescopes and efficient frame transfer time-series photometers will probably be required to undertake these campaigns, since the newly detected DBVs will undoubtedly be, on average, significantly fainter than those in the existing sample.

In summary, our work suggests that not only can we demonstrate the reality of the plasmon neutrino process, but we can also quantitatively constrain the production rates in the temperature-density domain relevant to white dwarf interiors.

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